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Uniform versus random orientation in fading and filling-in

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Abstract

V1 responses to an optimally oriented test line in the receptive field center may be modulated by placing lines of same or different orientations in the surround. While iso-orientation produces strong inhibition, cross-orientation enhances the response [Knierim, J. J., & Van Essen, D. C. (1992). Neuronal responses to static texture patterns in area V1 of the alert macaque monkey. *Journal of Neurophysiology, 67*, 961–980]. We looked for a perceptual correlate of neuronal texture modulation using perceived salience as well as fading and filling-in as response criteria. Two patterns by Vicario (1998) [Vicario, G. B. (1998). On Wertheimer's principles of organization. In G. Stemberger, (Ed.), *Gestalt theory,* (Vol. 20, pp. 256–270). Vienna: Verlag Krammer] served as targets. One consisted of randomly oriented bars in the center and uniformly oriented bars in the surround, while the other had bars of uniform orientation in the center and bars of random orientation in the surround. In spite of identical texture contrast at the boundary, the first pattern was judged more salient than the second and its center took more time to fade. When the surround was decreased in width, fading time followed no systematic trend and filling-in was increasingly replaced by filling-out. A higher salience and longer fading time for stimuli with a uniformly as opposed to randomly oriented surround was also obtained when the bars in the center were replaced by dotted arrays. However, no asymmetry was found for the converse patterns when dots were in the surround and bars in the center. Findings are interpreted in terms of stronger surround suppression exerted by randomly oriented bars as compared to uniformly oriented bars. Modeling suggests that this suppression may mediate a statistical computation by the visual system, aimed at detecting a texture boundary between the center and surround when the center texture was likely generated by a different random process than that which generated the surround.

Keywords: Textural filling-in; Orientation contrast; Perceptual salience; Fading time; Center–surround interaction; Filling-out

1. Introduction

With strict fixation visual targets quickly fade from view by assuming the brightness and color of the surround (Krauskopf, 1963; Troxler, 1804). This assimilative spreading is called filling-in (Gerrits & Vendrik, 1970; see Komatsu, 2006, for review). It also holds for stimuli composed of different textures (e.g., Ramachandran & Gregory, 1991).

Caputo (1998) studied filling-in in texture patterns of differentially oriented line elements, using a rectangular frame presented to the other eye as a mask. He found that for a uniform pattern, the region inside the mask appeared darker with only a few malformed line elements left, suggesting that the mask impeded texture filling-in. When the lines enclosed by the frame were rotated from iso-orientation to cross-orientation, they were fully preserved and the darkening was reduced, indicating that pop-out was not influenced by the mask. Caputo (1998) concluded that filling-in is subserved by two processes: an early stage for the spreading of mean luminance and

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a later stage for the spreading of texture from the surround into the target area.

Motoyoshi (1999) similarly found that an annulus, presented shortly after a textural stimulus, suppressed the enclosed texture except for odd elements and bars oriented orthogonally to the surround. This finding was taken as evidence that pop-out occurs prior to filling-in. It further prompts the assumption that fast spreading of textural activity during filling-in is based on long-range horizontal interactions in the visual cortex known to link cells with similar orientation preferences (Knierim & Van Essen, 1992; Wolfson & Landy, 1999). There are two approaches to textural figure–ground segregation and its role for fading and filling-in: neurophysiological and computational.

1.1. Neurophysiological approach

Although the neural basis of texture segmentation is still under debate, contextual information modulating the neural response is assumed to play an important role for the detection of texture borders and pop-out (Desimone, Moran, Schein, & Mishkin, 1993; Kastner, De Weerd, & Ungerleider, 2000; Nothdurft, Gallant, & Van Essen, 2000). Single-cell studies in primary and extrastriate visual cortex (V1, V4) show modulating influences from beyond the classical receptive field. For example, iso-oriented lines outside the classical receptive field exert stronger inhibition onto an optimally oriented line within the receptive field center compared to cross-oriented or randomly oriented lines (Kastner, Nothdurft, & Pigarev, 1999; Knierim & Van Essen, 1992; Nothdurft, Gallant, & Van Essen, 1999; Sillito, Grieve, & Jones, 1995). The less suppressive effect of the randomly oriented lines typically evoked larger neural responses of the center line, which are assumed to promote perceptual segmentation of a textural image (Gilbert & Wiesel, 1990; Knierim & Van Essen, 1992). Yet it is not clear, if surround effects are always suppressive compared to the response to the center stimulus alone, or if they can also be facilitatory (Ito & Gilbert, 1999; Kapadia, Ito, Gilbert, & Westheimer, 1995).

Stürzel and Spillmann (2001) investigated texture filling-in as a function of the perceptual salience of the stimuli. They used figures defined by orientation contrast, shape contrast, and order contrast. Salience, as measured by magnitude estimation and reaction time, was varied for each figure by altering the strength of the textural contrast between figure and ground. The authors found that perceptual salience increased with increasing texture contrast and both co-varied with the time required for fading and filling-in. They concluded that the salience of figure–ground segregation is an essential determinant of fading.

A look at the two texture patterns presented in Fig. 1 (reproduced from Vicario, 1998) confirms this conclusion. The pattern on the left consists of vertical bars in the center and bars of random orientation in the surround. The pattern on the right is the converse of the pattern on the left. Although the textural contrast between center and surround is the same, only in reversed order, both stimuli clearly differ in perceived salience, with the center on the right standing out more strongly than the one on the left. Because of this asymmetry, stimuli would be expected to yield different times for fading and filling-in. Indeed, Götzl (2004, unpublished) found in 32 subjects (16 male/16 female) that filling-in of the random center by the uniform surround took about twice as long (a total of 10.23 s) as filling-in of the uniform center by the random surround (5.18 s).

Pair 1

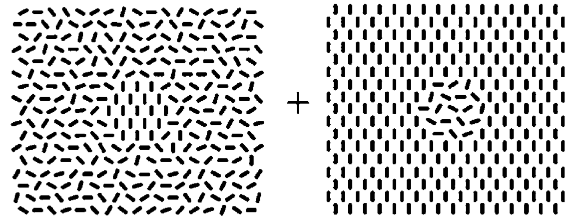

Fig. 1. Stimulus pair 1. Two texture patterns by Vicario (1998). The pattern on the left has randomly oriented bars in the surround and uniformly oriented bars in the center, on the right the textures are reversed. Note that the two patterns differ in perceptual salience and fading time as can be verified by fixating on the central cross.

To account for these differences, we therefore suggest that in a pattern having randomly oriented bars in the center and uniformly oriented bars in the surround (Fig. 1, right), suppression is likely to be weak and excitation from the center strong. Conversely, in a pattern having uniformly oriented bars in the center and randomly oriented bars in the surround (Fig. 1, left), suppression is likely to be high because of the larger number of activated channels and weak excitation from the center. Our results are consistent with these assumptions, showing higher salience and longer fading time for the random center and lower salience and shorter fading time for the uniform center.

1.2. Computational approach

Similar perceptual asymmetries as for the two Vicario patterns have been found in visual search tasks. For example, a study on orientation differences shows that it is easier to find a tilted item among vertical items than a vertical item among items that are all tilted in different directions (Foster & Ward, 1991). Search efficiency obviously depends on what is target and what surround (Treisman & Gormican, 1988). Some search asymmetries have been attributed to a more difficult search in the presence of more heterogeneous distractors (see Wolfe, 2001, for a review).

Rosenholtz (1999, 2001a) proposed that many search asymmetries were due to differences in experimental design, which inadvertently paired one target with more heterogeneous distractors, thus making it more difficult to find than another target. By comparing performance with a signal-detection theory (SDT) model of visual search, Rosenholtz (2001b) also found that distractor heterogeneity had a greater effect on search performance than predicted by an ideal observer. Rosenholtz (1999, 2001a) suggested that the reason for the strong effect of distractor heterogeneity is that it is beneficial for the visual system to detect statistical "outliers"; with more variable distractors, a target needs to be more distinct in order to be an outlier, i.e., to be likely generated by a different process than that which generated the distractors.

For modeling human pre-attentive texture segmentation, Rosenholtz (2000) suggested a related texture segmentation algorithm, in which textures segment if they differ *significantly* (in the statistical sense) in their first-order statistics of certain basic features. For instance, orientation-defined textures segment if they differ significantly in either their mean orientation or their orientation variance.

With regard to the two Vicario patterns used in this study (Fig. 1), differences in texture segmentation may be based on judgments on whether or not the distribution of features in the center of the pattern is likely to derive (i.e., as a subset) from the same distribution of features presented in the surround. The pattern with randomly oriented lines in the center (high variability) should therefore be more easily segmented from its background of uniformly oriented lines (low variability) because the probability that a few high variability feature samples could have derived from a low variability process is very low. Perceptual salience should therefore be higher for this pattern as opposed to the converse with randomly oriented lines in the background. In the latter case, a few low variability feature samples could quite plausibly have come from the same uniform process generating the background; thus in this case the center should more weakly segregate from the surround.

The neurophysiological and the computational approaches are not incompatible. Both the suggestion that contextual information modulates the suppressive (or facilitatory) effects of the surround, and the suggestion that the visual system computes statistical tests in order to find texture boundaries, amount to non-linearities in which the output is dependent upon the distribution of items in the surround. Hypotheses of non-linear suppressive effects of the surround are well grounded in neurophysiology, but it is less clear precisely what predictions these hypotheses make about the empirical results. On the other hand, Rosenholtz (2000) has shown that statistical computations can be accomplished using biologically plausible hardware, though the computations suggested by this work have not yet been grounded in neurophysiology.

2. Experiments

A total of three experiments were performed to test the influence of uniformly versus randomly oriented bars on salience and filling-in. In Experiment 1, we extended Götzl's (unpublished) study of the two Vicario patterns by surrounding the center with a ring enclosure as well as by reducing the width of the surround. We hypothesized that an explicit border between center and surround as well as a reduction of surround width would prolong fading time.

In Experiment 2, we tested 10 stimulus pairs derived from Fig. 1. In these stimulus patterns uniformly oriented or randomly oriented bars in the surround were presented in conjunction with dotted textures in the center. This was done to study the influence of differences in surround orientation on salience and fading time with the same stimulus in the center. Higher perceptual salience and longer fading times were expected for patterns with uniform bars in the surround because of the weaker surround suppression.

In Experiment 3, the same stimulus pairs were used, but with center and surround reversed, i.e., dots instead of bars in the surround. Random dots are supposed to produce only weak suppression effects (Li, Thier, & Wehrhahn, 2000). If surround suppression were crucial in determining salience and filling-in, little systematic difference in salience and fading time would be expected if uniformly versus randomly oriented bars were in the center and dots in the surround.

In a last step, we tested the fit of the experimental data derived from Experiments 1–3 with the predictions based on the texture segmentation algorithm of Rosenholtz (2000). We demonstrate that this model predicts many of the asymmetries we find in our experiments.

2.1. Methods

2.1.1. Subjects

Six subjects (three males, three females, aged 20–43 years) estimated perceptual salience while another group of 10 subjects (five males, five females, aged 22–29 years) determined fading time (except for Experiment 1, part 1, where there were only four subjects). All but three observers (including two of the authors) were naïve to the purpose of the experiments, although highly trained in fixation. Their visual acuity was normal or corrected-to-normal.

2.1.2. Stimuli

The two Vicario patterns (Fig. 1) and variants thereof (Figs. 5 and 8) served as stimuli. All experimental patterns were generated in Corel Draw 12 and consisted of bars versus dots in center and surround, except for stimulus pair 1 which had bars in the surround, but no texture in the center. Rectangular stimuli subtending an area of 9×11 deg of visual angle were presented on a 22×29 deg monitor screen. The diameter of the central disk was 3 deg in each case. The bars subtended 0.08×0.4 deg, while the diameter of the dots was 0.2 deg.

The luminance of the bars and dots was 16.5 cd/m^2 and the luminance of the background 94 cd/m^2, resulting in a Michelson contrast of 71%. Perceptual segmentation into center and surround was based merely on a texture-defined (i.e., implicit) boundary in the absence of any physical delineation (explicit border). Minor differences in element density as well as small imperfections at the interface between the two textures were deemed negligible.

2.1.3. General procedure

Stimuli were presented on a 21″ *Phillips 201B* CRT monitor (resolution 1024×768 pixels) with a refresh rate of 100 Hz. Two OSRAM L36 W/25 universal-white fluorescent tubes delivered 95 LUX at eye level. Subjects stabilized their head on a chin–forehead rest and fixated a cross from a distance of 72 cm with both eyes. The center of the stimuli was at 9 deg eccentricity on the right side of the cross. Only one pattern was shown at a time.

Perceptual salience was defined as the strength by which the central area of a stimulus pattern stands out from the background (try Fig. 1 for example). The degree of this perceived figure–ground segregation was measured using magnitude estimation. Subjects assigned a value between 1 and 9 to each stimulus pattern in accordance with the perceived strength of the texture contrast. Two texture stimuli served as references. The lower anchor (rating = 1) consisted of vertical bars in center and surround, i.e., a surface with no textural boundary, while the upper anchor (rating = 9) was composed of vertical bars in the center and horizontal bars in the surround, i.e., maximal texture contrast. Both anchors were periodically interspersed between the experimental stimuli as references for estimating perceptual salience. Stimuli were presented twice in a randomized order with only one pattern presented at a time. Exposure duration was unlimited.

The time for fading and filling-in was clocked electronically, starting at stimulus onset. Subjects pushed a button when the two textures in center and surround looked the same and could no longer be distinguished from each other. Subjects were instructed to describe the texture in the overall stimulus after fading had occurred (e.g., a surface with bars oriented uniformly or randomly throughout).

3. Experiment 1: Vicario patterns: Implicit versus explicit border

From the unpublished study by Goetzl and own informal observations we know that the pattern on the left of Fig. 1 fades and fills-in more rapidly than the one on the right. Here, we tested the idea that the border separating center and surround first needs to be perceptually leveled (i.e., fading) before filling-in can occur (DeWeerd, Desimone, & Ungerleider, 1998). This is in agreement with the theory of edge adaptation (DeWeerd, Gattass, Desimone, & Ungerleider, 2002) according to which filling-in occurs in two steps: adaptation to the edge of the target (“cancellation”) and subsequent neural spreading from the surround onto the target area (“substitution”). As there is only an implicit border separating center and surround in texture contrast stimuli, we predicted that fading and filling-in would take longer when a continuous line (explicit border) were used to delineate the center. Note that the simple measure of fading time did not enable us to disentangle the two processes of edge adaptation, “cancellation” and “substitution”, thus our predictions referred only to adaptation as a global process.

3.1. Procedures

To test our prediction, we presented the two patterns shown in Fig. 1 without and with an explicit border (not shown). In the latter condition the center was surrounded by a black ring of 0.08 deg in width. Time for fading and filling-in with and without the ring was measured twice for four subjects (including two of the authors).

3.2. Results

Under these conditions fading time for the delineated center increased by approximately 2 s from 12 to 14 s for the pattern with the random surround (Fig. 1, left) and from 16 to 18 s for the converse stimulus (Fig. 1, right).

3.3. Reduction of surround size

If a physical ring separating the center from the surround prolongs fading and filling-in, reducing the width of the surround may have the same effect. The first blocks the filling-in of surround features into the center by acting as a barrier to propagation, while the second reduces surround suppression onto the center. It therefore would be expected to prolong fading time.

3.4. Procedures

To test this hypothesis, we progressively reduced the width of the annular surround in the two Vicario patterns (Fig. 1), while the size of the disk-shaped center was kept constant. The reduction of surround width was done in three steps with patterns subtending 11, 6, 5, or 4 deg, respectively (Fig. 2). These sizes corresponded to four ratios between the number of bars in center and surround: 1/15 (Vicario pattern, pair 1), 1/5, 1/3, and 1/1 (pairs 2–4). The number of bars in the center was always 19. Stimuli were presented as before.

3.5. Results

Fig. 3 plots the times obtained for fading and filling-in for the four stimulus pairs used. Based on subjects' descriptions, two response modes for texture fading were distinguished, filling-in and filling-out. We use the term *filling-out* to denote the percept of texture spreading from the center onto the surround. In this condition subjects perceived the entire stimulus area as having the same texture as the center. According to this differentiation, we performed separate analyses for trials in which subjects perceived filling-in and trials in which they perceived filling-out.

For patterns with uniformly oriented bars in the center and randomly oriented bars in the surround (panel a), time for fading and filling-in increased little, if at all, from pair 1 to pair 4. In comparison, time for filling-out (panel b) changed substantially, being longest for pair 2 (>30 s), but much shorter for stimulus pairs 3 and 4 (there was no

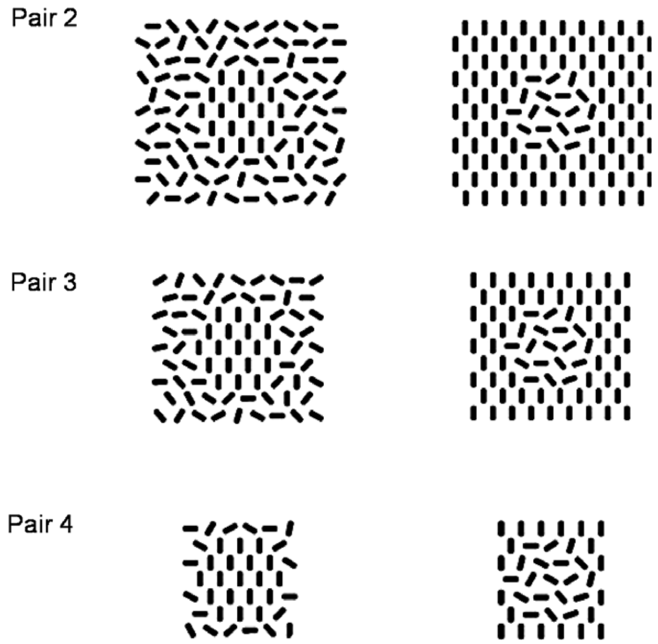

Fig. 2. Stimulus pairs 2–4. The centers are kept constant, while the surrounds are progressively reduced in width.

filling-out for stimulus pair 1). The time for filling-in of patterns with randomly oriented centers and uniformly oriented surrounds (panel c) shows no systematic trend for filling-in, but an abrupt decrease for filling-out (panel d).

Fig. 4 plots the frequency for filling-out as a function of surround width. For patterns with uniformly oriented centers and randomly oriented surrounds the curve for filling-out increases from 0% to 20%. For patterns with randomly oriented centers and uniformly oriented surrounds the curve for filling-out rapidly increases from 20% to 80%.

A non-parametric χ^2 test was done comparing the frequency of filling-in with the frequency of filling-out for the smallest pattern (pair 4) with either randomly or uniformly oriented lines in the surround. There was a trend in the direction of higher frequency of filling-out for patterns with randomly oriented centers and uniformly oriented surrounds (one-way $\chi^2(1) = 2.50$ (corr.), $p < .058$).

4. Experiment 2: Dotted centers with randomly versus uniformly oriented surrounds

Experiment 1 and previous work (Götzl, 2004, unpublished) has shown that a stimulus with randomly oriented bars in the center and uniformly oriented bars in the surround appears more salient and takes more time to fade than a stimulus with the two textures reversed. This is consistent with our hypothesis that the uniform texture in

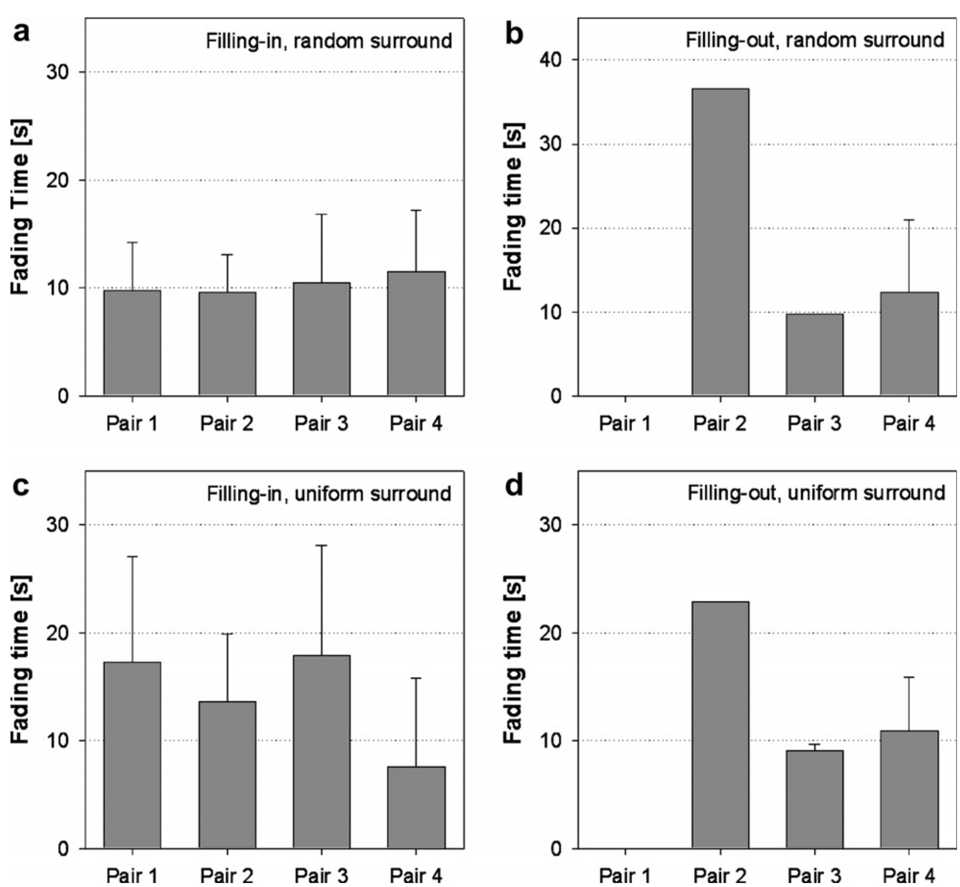

Fig. 3. Mean fading time for filling-in (panels a and c) and filling-out (panels b and d) plotted for stimulus pairs 1–4. The two panels on the top refer to uniform centers with random surrounds, the two panels at the bottom to random centers with uniform surrounds. No filling-out was reported for stimulus pair 1. Vertical bars give the standard deviation. Each column represents the averaged data of two measurements in each of 10 subjects.

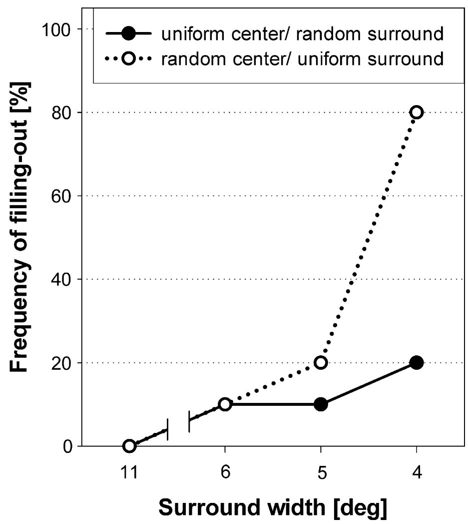

Fig. 4. Frequency of filling-out for stimulus pairs 1–4 plotted as a function of surround width. The dotted curve refers to stimuli with uniform centers with random surrounds and the continuous curve to random centers with uniform surrounds. Center/surround ratios were 1:15, 1:5, 1:3, and 1:1 bars corresponding to pattern sizes of 11, 6, 5, and 4 deg, respectively. Each datum point represents the percentage of the filling-out responses by 10 subjects.

the surround exerts less suppression onto the center, thus rendering it more salient. In this experiment we tested whether bars of random or uniform orientation would yield a similar asymmetry if tested with dotted textures in the center. This was done to study the influence of surround orientation on salience on one hand and fading and filling-in on the other when the texture in the center was kept constant.

4.1. Procedures

To this extent we compared perceptual salience and fading time for various dotted textures in the center with randomly versus uniformly oriented bars in the surround (Fig. 5). The dotted arrays in the center were modeled after the arrays used by Kubovy, Holcombe, and Wagemans (1998) and were common to both members of a pair. Dots were arranged randomly (pair 6), horizontally and obliquely (pair 7), or horizontally and vertically (pair 8). Stimulus pair 5 had a white center and served as a control (i.e., luminance contrast only). In addition, we again tested the two Vicario patterns (Fig. 1). Stimuli were presented as before.

4.2. Results

Ratings for perceptual salience are plotted in Fig. 6. Patterns with a randomly oriented surround (black columns) generally had a lower perceptual salience than patterns with a uniformly oriented surround (gray columns), irrespective of the dotted array in the center. A repeated-measures analysis of variance (ANOVA) revealed a significant main effect for the between-subject factor surround orientation ($F(1,5) = 18.04$, $p < .008$) and a significant main effect for the within-subject factor center arrangement ($F(4,20) = 16.32$, $p < .001$). In addition, there was also a significant interaction of both, surround orientation and center arrangement ($F(4,20) = 6.71$, $p < .001$). There was one exception. Stimulus pair 5, being devoid of a texture contrast, showed no difference between ratings for randomly versus uniformly oriented bars in the surround (ceiling effect). The high luminance contrast present in this pattern led to a strong perceptual segmentation of center and surround and produced the highest salience of all.

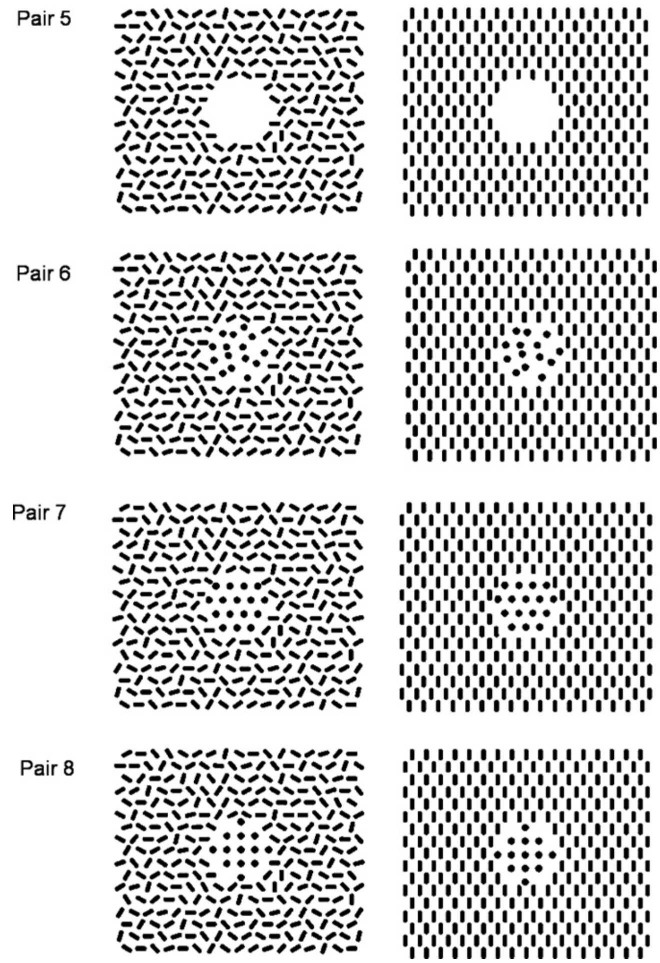

Fig. 5. Stimulus pairs 5–8. The dotted centers on the left and right are identical, but the bars in the surrounds are either randomly oriented (left) or uniformly oriented (right). Compare the patterns for perceptual salience and ease of fading and filling-in.

Fading time for these stimuli is plotted in Fig. 7. As we did not observe any filling-out effects for these patterns, fading time was always based on filling-in. Stimulus patterns with randomly oriented bars in the surround (black columns) faded significantly faster than patterns with uniformly oriented bars (gray columns). A repeated-measures analysis of variance (ANOVA) revealed a significant main effect for the between-subject factor surround orientation ($F(1,8) = 22.01$, $p < .002$) and a significant main effect for the within-subject factor center arrangement ($F(4,32) = 2.71$, $p < .0047$).

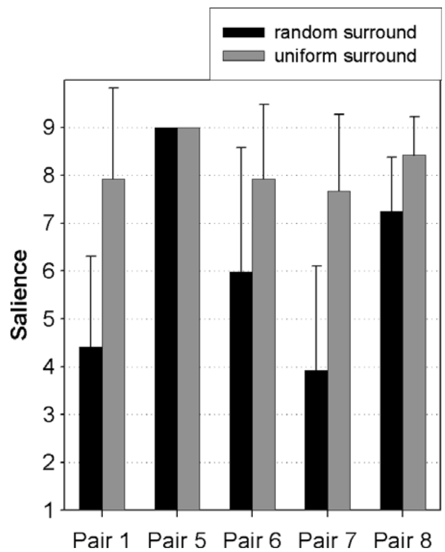

Fig. 6. Mean perceptual salience plotted for the stimulus pairs shown in Fig. 5. Black columns represent randomly oriented texture in the surround, while gray columns represent uniformly oriented texture. Vertical bars give the standard deviation. Each column represents the averaged data of two measurements in each of six subjects.

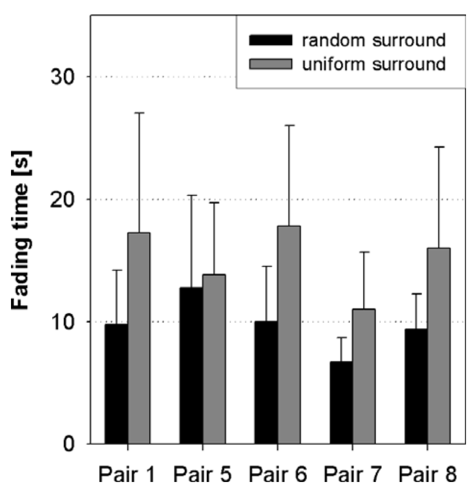

Fig. 7. Mean fading time plotted for the stimulus pairs shown in Fig. 5. For details see legend to Fig. 6. Each column represents the averaged data of two measurements in each of 10 subjects.

For easy visualization of the results go back to Fig. 5. Except for stimulus pair 5, salience was always lower and fading time shorter for stimuli on the left-hand side and higher and longer for stimuli on the right-hand side. These findings are consistent with a stronger suppression by the randomly oriented surround when the texture in the center of the stimulus pattern was the same in both pair members.

The difference in perceptual salience between the two members of each pattern was largest for stimulus pairs 7 and 1 (Fig. 6) and in fading time for stimulus pairs 6, 1, and 8 (Fig. 7). For the Vicario patterns (pair 1) we successfully replicated the finding by Götzl (2004, unpublished), with an even greater difference in fading time (a total of 7.54 s in our study versus 5.05 s in Götzl's study). Note also that for stimulus pair 5, salience was considerably higher than for all the other stimuli, whereas fading time for this stimulus pair was in the same range as that for the others.

When fading time was plotted as a function of perceptual salience, the curve increased monotonically with increasing salience for stimuli with randomly oriented surrounds (one-tailed Pearson's correlation: $r = 0.84$, $p < .005$). There was little difference for stimuli with a uniform surround (not shown).

5. Experiment 3: Dotted surrounds with randomly versus uniformly oriented centers

The previous experiment showed that a stimulus pattern with dots in the center and uniformly oriented bars in the surround, appeared more salient and took more time to fade than a stimulus with the same dotted center, but randomly oriented bars in the surround. Here, we asked whether an analogous difference would be obtained when center and surround texture were reversed.

5.1. Procedures

Perceptual salience and fading time were measured as before for stimulus patterns with dots in the surround and randomly versus uniformly oriented bars in the center (Fig. 8). The dotted arrays in the surround were again common to both members of a given pattern (pairs 9–11).

5.2. Results

Perceptual salience for all three stimulus pairs is plotted in Fig. 9. There was no systematic difference in salience between patterns with randomly or uniformly oriented bars in the center and the same dotted textures in the surround. Salience was the same for the two members of stimulus pair 9. For pair 10, the uniformly oriented center was more salient, whereas for pair 11 the opposite was the case. A repeated-measures ANOVA showed no significant main effect for the between-subject factor center orientation ($F(1,5) = 0.26$, $p < .635$), but a significant interaction of both main effects, center orientation and surround arrangement ($F(2,10) = 7.67$, $p < .001$).

Fading times for these stimuli are plotted in Fig. 10. Again, no filling-out effects were reported and fading time always refers to filling-in. For pairs 9 and 10, the uniformly oriented bars in the center (gray columns) required more time for filling-in than the randomly oriented bars (black columns), while for pair 11 the opposite was the case. None of these differences was significant ($F(1,9) = 0.26$, $p<.621$) Note that fading time differs for the two members of stimulus pair 9, although both were judged equally salient (Fig. 10).

6. Modeling of the data

We compared our experimental results with the predictions of the computational modeling approach based upon

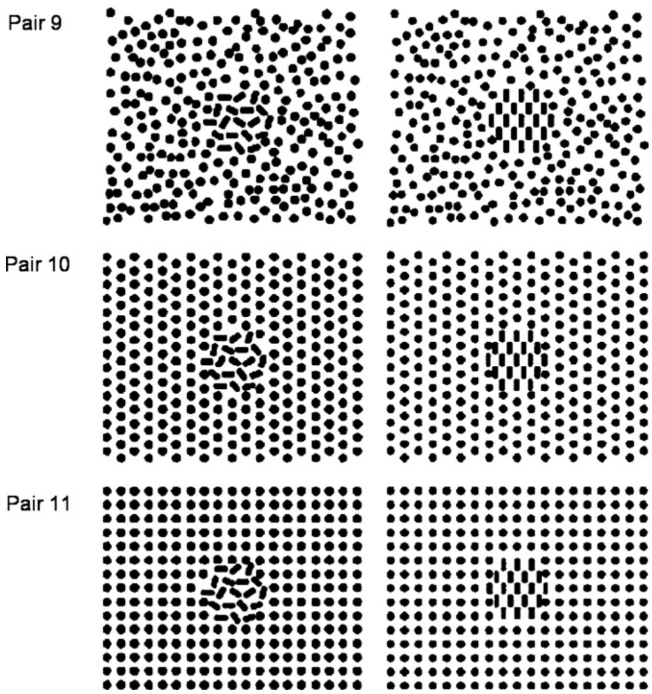

Fig. 8. Stimulus pairs 9–11. The surrounds on the left and right are identical, but the bars in the center are either randomly (left) or uniformly oriented (right).

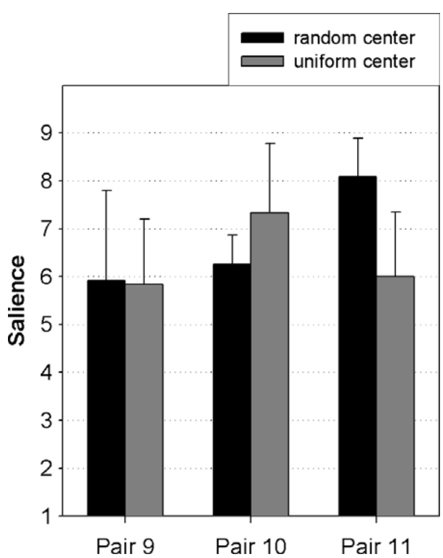

Fig. 9. Mean perceptual salience plotted for stimulus pairs 9–11. Black columns represent randomly oriented texture in the center, while gray columns represent uniformly oriented texture. Vertical bars give the standard deviation. Each column represents the averaged data of two measurements in each of six subjects.

the texture segmentation algorithm of Rosenholtz (2000). This model consists of several stages: the observer extracts estimates of various features such as orientation and contrast energy from an image, at a number of spatial scales. For the stimulus patterns in this paper, orientation was typically the only relevant feature, so we show results only for orientation edges. These orientation estimates have added internal noise with standard deviation, s. The observer then locally pools these orientation estimates, essentially taking n samples from each side of a possible edge. Here we used parameter settings as in Rosenholtz (2000). If the two sets of samples differ significantly in mean orientation or orientation variance, the observer sees an edge and segregates the two textures.

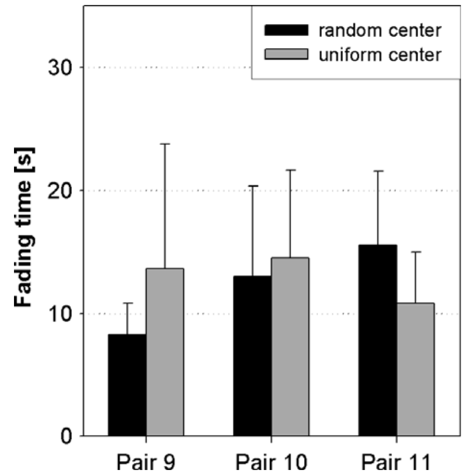

Fig. 10. Same as in Fig. 9, but for mean fading time. Each column represents the averaged data of two measurements in each of 10 subjects.

Applied to our data, stimuli were tested for both their mean orientation and their orientation variance, As expected, the algorithm revealed essentially no relevant edges due to differences in mean orientation. In contrast, testing the stimuli for any differences in their orientation variance revealed stronger edges for the patterns with uniformly oriented bars in the surround and randomly oriented bars or

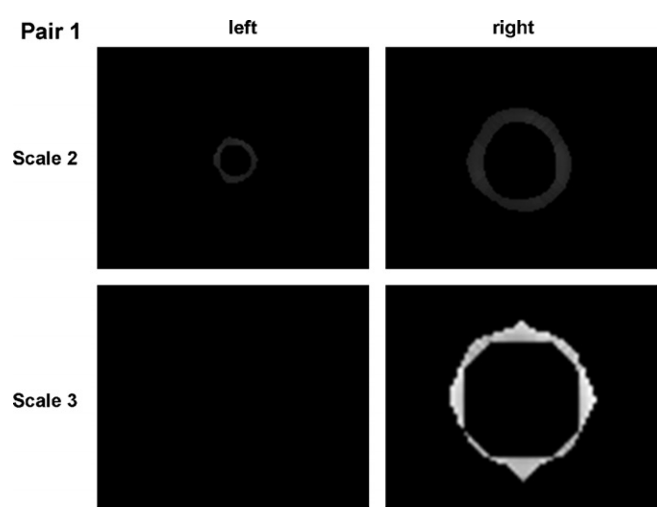

Fig. 11. Texture edges computed by the segmentation algorithm of Rosenholtz (2000). Orientation and texture boundaries are found at three different scales from fine (scale = 1) to coarse (scale = 3). The edge strength in pair 1 (left, scale 2) is weaker (about 5.0) than in pair 1 (right, scale 2) (about 5.5), though this difference is not easily visible in the edge images. The edge strength for pair1 (right, scale 3), on the other hand, is about 23, much higher. And of course there is no edge in pair 1 (left, scale 3). So overall the prediction is greater segmentation for the right side of the pair.

dots in the center. For pair 1, the uniform surround pattern led to a slightly stronger edge than the random surround at the nominal scale of the texture, and to a much stronger edge at a coarser scale. Fig. 11 shows an example of the output from the texture segmentation algorithm for this pair. Pairs 2–4 showed progressively weaker edges for the pattern on the right-hand side, indicating that the uniformly oriented surround of the Vicario patterns was more strongly affected by the reduction in size. For pairs 5–8, the algorithm detected strong edges for the right patterns with uniformly oriented surround, but nearly invisible edges for the left patterns, aside from the contrast edge for pair 5. This is in good agreement with our experimental data. Pairs 9–11 showed only weak texture edges between center and surround for the textures on the right, and essentially no texture edges for the patterns on the left. In general, stronger orientation edges detected by the texture segmentation algorithm were closely related to prolonged times for fading and filling-in for these patterns.

7. Discussion

In this study, we compared the influence of different textures in center and surround on perceptual salience and time required for fading and filling-in.

First, we studied the effect of an implicit versus an explicit border on fading and filling-in, using patterns with short bars of uniform orientation in the center and bars of random orientations in the surround or vice versa (Fig. 1). When we surrounded the center of stimulus pair 1 with a thin black ring (explicit border), we found that fading time was about 2 s longer than without the ring. The extra time apparently was needed for cancelling the explicit boundary (Spillmann & De Weerd, 2003).

So far, we had tacitly assumed that a textural or implicit border is equivalent to a continuous border between center and surround. Indeed, DeWeerd (personal communication) suggests that the contrast between two spatially contiguous textures may constitute a perceptual barrier that is functionally similar to a physical (continuous) border delineating two surfaces of different luminance or wavelength. Our results revealed approximately the same relative differences in fading time for the Vicario patterns with explicit and implicit borders. This was consistent with the idea by DeWeerd and coworkers (1998) suggesting that the implicit border—although weaker—requires the same two mechanisms, border cancellation and feature substitution, for fading and filling-in.

In addition to these edge adaptation processes, surround width was assumed to affect the time for fading and filling-in. Li et al. (2000) demonstrated that the neural response to a test line decreased with increasing area of surround texture, suggesting more lateral inhibition. Accordingly, one might expect that the influence of the surround onto the center decreases as the surround is rendered progressively narrower. Indeed, DeWeerd et al. (1998) found shorter fading times with decreasing surround width when center size was kept constant.

Contrary to prediction, Fig. 3 shows fading time to be largely the same for all stimuli with a randomly oriented surround and a uniformly oriented center (panel a). This suggests that in our experiment surround size was not much of a factor for filling-in. No systematic change was obtained either with a uniformly oriented surround and a randomly oriented center (panel c). These results are consistent with the findings obtained in experiments on pop-out (Nothdurft, 1992), suggesting that the crucial factor was the texture contrast at the interface. On the other hand, we found a clear decrease of time required for filling-out (panels b and d). Fig. 4 plots the frequency of occurrence for filling-out as a function of surround width. Whereas the frequency of filling-in decreased with decreasing surround width, the frequency of filling-out increased. This is particularly pronounced for the patterns with a randomly oriented center and a uniformly oriented surround. Here, the greatest change occurred for the pair with the narrowest surround width (stimulus pair 4).

Filling-out has been reported before by DeWeerd, Desimone, and Ungerleider (1998) for texture and by Shimojo, Wu, and Kanai (2002, 2003) and Hamburger, Prior, Sarris, and Spillmann (2006) for color. According to DeWeerd et al. (1998), filling-in is a bi-directional process of feature spreading whereby the relative sizes of a textured surround and an enclosed gray target determine which region becomes filled-in by the other. Here we demonstrate that this also applies to texture patterns composed of differently oriented line elements. Conceivably, with a narrower surround the suppressive effect on the central target becomes too weak and texture spreading reverses in direction from inward to outward, perhaps in the interest of a simpler figure–ground segmentation. Shimojo, Wu, and Kanai (2003) put forward a similar argument for color spreading-out.

In Experiment 2, we studied the influence of different textures in center and surround on perceptual salience and time for fading and filling-in. For the Vicario patterns (Fig. 1) the local texture contrast at the boundary was the same in both cases. Accordingly, one might assume that the perceived salience of figure–ground segregation and the time required for fading and filling-in would also be the same. However, this was not so. Perceived salience was significantly higher and fading time longer when the randomly oriented texture was in the center and the uniformly oriented texture in the surround than the other way around. This difference confirms the earlier observations by Götzl (2004, unpublished) and cannot be attributed to a difference in mean luminance. It must be a genuine effect of texture contrast.

In a next step, we compared randomness versus uniformity of texture elements in the surround with a common array of dots in the center. As for the Vicario patterns, perceptual salience for all stimulus pairs was lower and fading time shorter, when the bars in the surround were randomly oriented (Fig. 5, stimulus patterns on the left).

The observation that a randomly oriented surround suppresses dots more strongly than a uniformly oriented surround (Fig. 5, right) may be attributed to the greater total neuronal activity available after pooling of the underlying line elements. The stronger signal lowers salience, thus rendering the center more susceptible to fading and filling-in.

Our assumption that different amounts of activity arising from the two kinds of surround texture account for our results is consistent with Sakaguchi (2001) who studied target/surround asymmetry for disk-ring patterns differing in grating orientation, spatial frequency, luminance, and color. Time for fading and filling-in increased with an increase in difference between the featural properties of target and surround (i.e., *feature difference effect*).

The results of Experiment 2 further suggest that surround activity elicited by the orientation contrast of the line elements dominates the center with regard to perceptual salience and filling-in. No systematic difference was found for patterns with dots in the surround and randomly or uniformly oriented bars in the center. Hence, different texture orientations in the center seemed to have little consequence for perceptual salience and fading and filling-in when they are juxtaposed to (non-oriented) dotted arrays.

Computational studies (e.g., Grossberg & Mingolla, 1985; Raizada & Grossberg, 2000) have focused on neural models of texture boundary detection that emphasize the importance of competitive and cooperative interactions in the boundary system. According to this model, grouping may occur by recurrent interaction between V1 complex cells and V2 bipole cells. More recently, Thielscher and Neumann (2005) emphasized the role of V4 cells that respond to orientation discontinuities for inputs from area V2.

Applied to our data, we suggest that texture patterns with uniform surrounds lead to stronger V2 groupings of the line elements at the border which in turn lead to stronger V4 activation and better textural border detection. Feedback mechanisms further enhance the V2 activations at the border which strengthen the resultant boundaries and thus prolong fading time. This is in line with our modeling data. The texture segmentation algorithm (Rosenholtz, 2000) revealed overall stronger edges for the textures with a uniform surround. This can be thought of as due to stronger grouping of the uniformly oriented line elements in the surround, and, as a result, a stronger boundary between center and surround, as it is more likely that the random center does not belong to the same group.

How the predictions made by search paradigms can be accounted for by the known properties of receptive fields of V1 neurons (Kapadia, Westheimer, & Gilbert, 2000; Li & Gilbert, 2002) is yet to be shown. Indeed, those properties typical apply to a single element in the receptive field center, whereas the textural stimuli used here had many such elements in the center. Both approaches, the neurophysiological and the computational, would therefore be served if the two Vicario patterns were used as stimuli for single cell recording. In this sense, our psychophysical results present a challenge to the neurophysiologist, as does the success of the computational model.

8. Conclusions

Our results suggest that for the texture patterns used in this study the neural activities in the surround, elicited by randomly or uniformly oriented bars, determine perceptual salience and fading time. With fixation, a randomly oriented texture in the center enclosed by a uniformly oriented texture in the surround stands out more strongly and persists longer than a uniformly oriented center enclosed by a randomly oriented surround. We varied these surround effects by systematically reducing surround size of the textural stimuli. Aside from filling-in, we observed a spread of texture outward from the center, when the surround became too narrow and the random texture in the center took possession of the uniform texture. We call this effect *filling-out*. A comparison between patterns having randomly or uniformly oriented bars in the surround and various dotted arrays in the center or vice versa further strengthens our assumption that filling-in is strongly related to the salience of the perceived texture segmentation boundary in these patterns, which is also mirrored by our modeling results. This process likely reflects a neural pattern which is triggered by the distributions of stimulus orientation in nonclassical receptive fields.

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